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Overview of solar technologies for electricity, heating and cooling production

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ABSTRACT

The efficient use of local renewable energy sources is a key factor to reach the EU's targets on climate change and renewable energy. In this review, the available technologies to convert solar energy into electrical and thermal energy are investigated. Photovoltaic panels, thermal collectors, heat pumps, solar cooling and energy storage systems are analyzed with a particular attention to their market availability for small-scale applications. Different ways to provide heating, cooling and sanitary hot water from solar source are analyzed and compared from an efficiency, economic and environmental perspective.

1. Introduction

In the Horizon 2020, the European Commission defined the strategy for a 'smart, sustainable and inclusive growth' and identified renewable energies as the basis of this development, setting three important goals to be achieved by 2020: 20% cut in greenhouse gas emissions compared to 1990 levels, enhance the energy savings by 20% and 20% increase of renewable energy consumption. The European Directive 2009/28/EC, provides the framework for 'the promotion of the use of energy from renewable sources' and establishes the objectives to be achieved by each EU Member State, while the measures for the enhancement of the energy efficiency are provided in the 2012/27/EU Directive. An other important step towards the 2020 targets is represented by the European Directive 2010/31/EU [1] on the energy performance of buildings, which points out the importance of reducing energy consumption and promotes the use of renewable energy sources in the building sector. Buildings account for 40% of total energy consumption in the European Union and this percentage is likely to increase, due to population growth, enhancement of the comfort levels and services provided, as Perez-Lombard et al. [2] underline in their survey of building energy consumption.

In 2015, new objectives for 2030 have been approved: 40% cut in greenhouse gas emissions compared to 1990 levels, 27% share of renewable energy consumption and 27% energy savings. The central role of renewable energy is then evident.

This review focuses on solar energy and aims at analyzing the application of solar renewable energy systems for the production of electricity, heating and cooling, to guarantee the best service to the end-user while ensuring optimal energy conversion and usage, based on the best available technologies. Various studies are available in literature which describe the different options to produce electrical and thermal energy from solar energy. Solar technologies are mainly analyzed in terms of efficiency and installation costs. Sarbu et al. [3] provide a detailed technical description of the different solar systems (solar PV, solar thermo-electrical, solar thermo-mechanical and solar thermal cooling). Similarly, Lazzarin [4] describes solar electrical and thermal solutions, comparing the different options based on the overall system efficiency and the investment cost. In 2008, according to the economic analysis carried out by Kim et al. [5], solar thermal cooling was representing an attractive solution. However, due to the severe reductions in the prices of PV systems and the increase in heat pump efficiencies, a more recent analysis carried out by the same authors in [6], shows solar electric as an interesting option from both an economic and efficiency point of view. This conclusion is in agreement with the projections of Otanicar et al. in [7]. While previous studies focused on the use of solar technologies for cooling purposes, this work will tackle the analysis of solar systems by comparing their suitability for different applications as well as widening the range of possible alternatives based on recent market trends; with hybrid systems which are gaining more attention.

Moreover, in spite of the wide variety of studies on solar technologies, only few of them analyze the environmental impact of the different options to convert solar energy into electrical and thermal

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energy. The contribute of each renewable energy system to the emissions is usually evaluated on its own by different authors and based on different assumptions, making more difficult the comparison of different technologies. Even though, the life cycle assessment (LCA) methodology to determine the environmental impact of a certain process or product is described in the ISO 14040:2006, there are no strict guidelines, leaving the choice of functional unit (i.e. the reference to which all data are normalized) and boundary conditions up to the user. Thus, one or more process steps (manufacturing, installation, maintenance and decommissioning phase) can be excluded from the analysis. This work aims at summarizing the findings of more than one hundred scientists, not only to provide an updated state-of-the-art of the various systems, which could be a baseline for non-specialist in the solar renewable energy field, but also to compare the various conversion process chains from different perspectives, so to provide readily available information for decision making process.

The study is organized in two parts. In the first section, the different solar technologies and storage systems are individually described, underlying advantages and disadvantages, while in the second part, various combinations of photovoltaic systems and solar thermal collectors with heat pumps and solar cooling technologies are compared in terms of conversion efficiency, environmental impact and installation cost. Additionally, different possibilities to integrate appropriate storage media are evaluated. Storage systems in combination with solar technologies allow to increase the amount of self consumed energy and guarantee a more continuous supply, ensuring better matching between electrical power generation and demand, consequently reducing power fluctuations and risks of over-voltage/under-voltage. The stochastic nature of renewable sources and the forecasted increase in penetration of distributed energy systems highlight the importance of a better integration of renewable energy generation. The energy produced by high penetration of renewables cannot be passively injected into the grid without jeopardizing the grid safety and reliability. In this scenario, the relevance of storage and energy management systems rises, leading to the development of the concept of microgrid [8]. Sechilariu [9] defines a microgrid as a "form of decentralized energy production, able to operate grid-connected and off-grid. …The microgrid controls on-site generation and power demand to meet the objectives of providing local power, ancillary services and injecting power into the grid if required."

This developing trend shall be taken into account in the analysis of the different solar renewable energy technologies and their flexibility, when integrated in a microgrid, shall also be assessed.

2. Solar thermal and electrical systems

Solar energy is the most abundant and inexhaustible source of energy. The interest in developing efficient technologies to convert solar energy into electricity or thermal energy has been increasing, since the energy crisis in the 1970s. The state-of-the-art of both thermal and electrical solar systems shall be considered in this section. The term solar thermal refers to those systems which convert solar energy directly into useful heat, which is transferred to a specific medium. An example of these systems are thermal collectors. The term solar electrical, on the other hand, refers to those strategies which allow the conversion of solar energy into electricity. Photovoltaic panels are the most known example of solar electrical systems. Other alternatives are available, such as thermal collectors coupled with a Stirling engine or a Rankine cycle. However, these systems will not be discussed in this paper and the reader is referred to the work by Zeyghami et al. [10]. Section 2.1 and 2.2 describe the different types of thermal collectors and photovoltaic cells and advantages/disadvantages of the respective systems are highlighted.

2.1. Solar thermal collectors

Solar collectors are particular types of heat exchangers, which absorb the solar radiation and convert it into useful heat transferred to a working fluid. A wide variety of thermal collectors is available on the market. They can be classified in two main groups: non-concentrating and concentrating. The latter consist of a reflecting surface which focuses the solar radiation to a smaller area. The ratio between the aperture area and the absorber area is known as concentration ratio. In non-concentrating collectors, the intercepting area coincides with the absorbing area. Thus, the concentration ratio is equal to 1. Flat plate collectors (FPC) and evacuated tube collectors (ETC) belong to this group, while compound parabolic (CPC), parabolic trough (PTC), linear fresnel reflectors (LFR) and parabolic dish (PDC) are examples of concentrating collectors.

A FPC consists of an absorber plate integrated with passages to transfer the heat from the absorber to the working fluid. In order to minimize the heat losses, an insulation material is placed at the bottom and a transparent cover on the top, ensuring low radiative emissions through a proper choice of the cover material. Usually glass is used because of its high transmittance of up to 90% of the incident solar short-wave radiation and the low transmittance for long-wave radiation emitted by the absorber. Both beam and diffuse radiation can be absorbed and no tracking system is required. This collector type is widely used in domestic applications due to the very low maintenance required and its operating temperature (30–80 °C), relatively low, if compared to other collector types, but suitable for both space heating and Domestic Hot Water (DHW). The best performance is obtained under warm climatic conditions, when the temperature difference between the thermal fluid and the ambient is low. This occurs since high temperature differences increase the thermal losses with a consequent reduction of the collector efficiency. Very high temperature and radiation, instead, expose to the risk of overheating. Flat plate collectors can be further subdivided as glazed or unglazed. Unglazed air collectors are suggested by Collins [11] as an interesting option to produce pre-warmed air used in HVAC systems, significantly reducing the heating load. Glazed collectors instead are suitable for domestic hot water production and can be single or double glazed depending whether one or two covers are used to further reduce the thermal losses. Flat plate collectors can also be classified based on the working fluid, usually air or water. The latter ensures a better heat transfer, but in cold regions a mixture of water with antifreeze has to be employed, even though with the development of polymeric collectors the use of antifreeze is often no longer needed [12]. The effect of using alternative working fluid on the collector performance has been widely investigated. A review is provided by Al-Shamani [13], that analyzes the use of nanofluids for both solar thermal collectors and photovoltaic/thermal (PV/T) systems.

Even if the performance of FPC has been improved through the use of selective coating, better performance in cloudy and cold conditions is ensured by evacuated tube collectors (ETC). These consist of a heat pipe surrounded by a vacuum tube, which reduce the thermal energy losses. The pipe contains a fluid (methanol) which, due to the solar radiation evaporates moving to the condensing region, where the accumulated heat is released and transferred to a second fluid. Due to gravity, the condensed vapor moves back to the evaporating section, restarting the cycle. Similarly to what occurs in FPCs, both direct and diffuse solar radiation can be absorbed and no tracking system is needed. However, due to the lower conduction and convection heat losses, the outlet fluid temperature of ETC can be higher.

Among the concentrating solar collectors, compound parabolic (CPC) are the only one that allow to concentrate both the direct and the major part of the diffuse radiation incident on the aperture. They consist of a parabolic reflector which conveys the radiation from the aperture to the absorber. CPC produces high outlet temperatures of 200–250 °C, making them suitable for enhanced heating applications. However, higher maintenance and manufacturing costs, with respect to FPC and ETC, limit their diffusion in the residential sector.

Parabolic trough collectors (PTC) consist of a reflective parabolic trough which concentrates the direct solar radiation to a tubular

Table 1
Solar thermal collectors [14–16].

Technology	Collector type	Concentration ratio	Typical operating temperature (°C)	Tracking System
Non concentrating	Flat Plate Collector (FPC)	1	30–80	No tracking system
	Evacuated Tube Collector (ETC)	1	50–200	No tracking system
Concentrating	Compound Parabolic Concentrator (CPC)	1–5	60–240	regular adjustment
	Parabolic Trough Collector (PTC)	15–45	60–400	One Axis
	Linear Fresnel Reflector (LFR)	10–40	60–250	One Axis
	Parabolic Dish Collector (PDC)	100–2000	100–500	Two Axis

receiver surrounded by a vacuum glass cover. Only direct radiation is concentrated thus making the use of one axis solar tracking system a necessity. This system ensures higher efficiency at high working temperatures but it is characterized by high installation and maintenance costs.

Linear Fresnel Reflectors (LFR) are more economically-feasible than PTC, due to the lower manufacturing cost and simpler structure with fewer rotating high pressure components. In fact, LFRs consist of a fixed receiver and a number of flat reflectors, but their optical efficiency is lower than that of PTCs.

Parabolic dish collectors (PDC) are composed of a concave mirror which concentrates the direct solar radiation in a single point receiver and use a two axis solar tracking system which constantly tracks the sun. This enables to reach very high outlet fluid temperature of up to 500 °C. Table 1 summarizes the main characteristics of each collector type.

Except for CPC which are used for enhanced heating applications, concentrating solar collectors are mainly used for electricity production, coupled with Stirling engine or Rankine cycle, in medium large scale power plants. Nevertheless, the trend of designing concentrating collectors for small scale application is increasing. A review, on the application of PTC in solar cooling systems is provided by Cabrera et al. [17] and by Jebasingh and Herbert [18], while a residential solar thermal power plant for electricity production, based on the use of a parabolic trough, has been patented by Bennett [19].

In spite of this new trend, according to the International Energy Agency (IEA) [20], FPC and ETC are still the most commonly used for domestic purposes. According to Ghafoor et al. [21], the costs of FPC and ETC are of 150–200 €/m^2 and 250–300 €/m^2 respectively, but the prices are expected to decrease due to the expanding influence of the Chinese market. Considering the worldwide market, ETC have a share of 71.1%. This result is mainly influenced by the increasing number of vacuum tubes installed in China.

In the European Union the trend is opposite, FPC dominates the market with a share of 83.8% while ETC accounts for only 11.4%, air collectors 1.2% and unglazed water collectors 3.6%. This trend is confirmed by the new installed capacity in 2014. According to the 2016 Report of the International Energy Agency (IEA) [20], the total installed capacity of solar thermal systems in 2014 was 409 GW_{th}: 63% for domestic hot water production (DHW) in single-family houses, 28% for DHW in multi-family buildings, 6% for swimming pools, 2% for both heating and DHW while the remaining 1% is used for other purposes like industrial processes, solar cooling applications, heating network etc.

From a thermodynamic point of view, the performance of FPC and ETC can be compared based on their efficiency (η), defined as the ratio between the heat transferred to the fluid and the incident radiation.

$$\eta = \eta_0 - a_1 \frac{\overline{T_f} - T_{air}}{G_c} - a_2 \frac{(\overline{T_f} - T_{air})^2}{G_c} \tag{1}$$

where η_0, a_1 and a_2 are determined through experimental tests and provided by the manufacturer. η_0 represents the optical losses which accounts for the solar radiation lost due to reflection and absorption. The linear and quadratic coefficients a_1 and a_2 consider the heat dissipated to the surroundings. $\overline{T_f}$ indicates the average fluid temperature ($(T_{f,i} + T_{f,u})/2$) according to the European standard, while it represents the collector inlet fluid temperature for the American standard. As Eq. (1) highlights, the efficiency also depends on the solar irradiance and decreases at a faster rate under low radiation condition.

The benefits of flat plate collectors for DHW, compared to electric and gas heating have been widely investigated, [22,23]. Kalogirou et al. [22] highlight the economical and environmental advantages of thermosiphon solar water heaters compared to conventional systems. An accurate life cycle assessment analysis (LCA) of a FPC has been carried out by Ardente et al. [24]. The authors considered the energy and materials involved in all the different phases, from the production process to the installation, maintenance and decommissioning. The collector considered in the analysis is a FPC having a total net surface area of 2.13 m^2. The values calculated by the author refer to the collector itself, rather than being referred to the collector surface area or to the energy output, in order to avoid misleading results. As underlined by the authors, the strong dependency of the energy output on the climatic conditions would determine different eco-profiles of the same collector depending on the location, and the lower specific environmental impact of collectors with a larger surface area does not necessarily correspond to a lower effective global impact. The values of global warming potential (GWP), acidification (AP), ozone depleting potential (ODP), nitrification (NP) and photochemical ozone creation potential (POCP) estimated by the authors are reported in Table 2.

Unlike FPC, only a few studies evaluate the environmental impact of ETC. The analysis, carried out by Lamnatou et al. [25] on building integrated flat plate and evacuated tube collectors, shows the superior benefits of the latter in terms of both energy payback time (EPBT) and greenhouse gas payback time (GPBT). For the EPBT, a value of 0.5 is obtained for ETC rather than 1.8 required for FPC. These values can be further lowered respectively to 0.1 and 0.5 through a proper recycle of used materials. As concerns GPBT, the values range from 1.4 to 13.4 years for FPC and 0.5–4.1 years for ETC, depending on the system boundaries considered for the LCA analysis.

2.2. Photovoltaic systems

In contrast to solar collectors, photovoltaic (PV) systems convert sunlight into electrical energy. A generic PV system consists of PV panels connected in series or parallel, a maximum power point tracker (MPPT) which allows to operate at the maximum power adjusting the reference voltage and an inverter that converts the direct current (DC) generated by the PV array, into alternating current (AC) which can either be injected into the grid or used in situ. Considering the

Table 2
Eco-profile of a flat plate thermal collector, [24].

Environmental Index	Thermal Collector
GWP [$kgCO_2$]	721
AP [$kgSO_{2eq}$]	5
ODP [$\mathrm{kgCFC-11_{eq}}$]	negligible
NP [$kgPO_{4eq}^{-3}$]	0.7
POCP [$\mathrm{kgC_2H_{4eq}}$]	.5

increasing market penetration of PV systems and the growing number of DC-based devices in residential buildings (i.e. computers, florescent lights etc.), many researchers have also considered whether DC-wired houses would provide any advantage compared to the traditionally AC-wired. The enhancement in terms of efficiency which could be obtained as well as the barriers to this transition are described in the work by Glasgo et al. [26].

Even though the photovoltaic effect was discovered by Bequerel in 1839, it was only in 1954 that the first silicon cell with an efficiency of 6% was produced, experiencing a fast developing process due to interesting applications in space programs. The crisis of the 1970s and the increasing attention to environmental problems and climate changes further promoted the development of this technology. Nowadays, the PV market is growing at a rate of 25% with an installed capacity of 50 GW in 2015, reaching a global electrical production of 227.1 GW [27].

A number of reviews on the different photovoltaic technologies is available in literature [28–30]. According to Razykov et al. [29], it is possible to distinguish between three generations of PV cells: the first generation refers to crystalline silicon; thin film technologies represent the second generation, which comprises CdTe, Ci(G)S and a-Si; the third generation includes PV cells based on double, triple junction, nanotechnology and organic materials.

Silicon is the raw material of the first generation solar cells. Its high availability and non-toxicity together with the good properties as semiconductor and stability under external ambient conditions favoured its usage. Monocrystalline silicon cells are manufactured from a large cylindrical single-crystal silicon ingot produced through the Czochralski process, which is then cut into layers. In this stage, almost 50% of the high purity silicon is wasted [31]. Afterward, the obtained layers are doped adding boron or phosphorus. This is a commercially mature photovoltaic technology, with the highest efficiency among the traditional cells currently available on the market. However a thick layer of silicon is needed due to the low absorption coefficient. The high amount of material required and the manufacturing process itself, which produces a considerable amount of wasted silicon, are responsible of the higher cost of the final product.

Polycrystalline silicon cells instead, are produced from blocks of silicon, which are first melted and then solidified obtaining crystals with different orientation. The manufacturing process is less complex compared to Mono-crystalline and the amount of wasted silicon is also reduced with a consequent lower final cost. However, due to the multi-crystalline structure and the presence of more defects, the efficiency is also lower. Thus, larger areas are required for the same amount of energy output.

In order to lower the cost as much as possible, optimization of the material usage is a key factor and represents the main reason for the intensive research activity on thin film solar cells. Due to the higher absorption coefficient, thin film technologies require a lower amount of semiconductor material compared to crystalline silicon. Silicon is deposited in thin layers on a substrate (usually glass or stainless steel). The layer is only of few micron, typically less than 10 μm, that is at least one hundred times thinner than a crystalline silicon panel [28]. This determines a reduction in the total costs due to lower material use and lower manufacturing costs while simultaneously obtaining more flexible and lightweight cells. Among the thin film cells, three types are commercially relevant: multiple-junction amorphous silicon cell (a-Si), copper indium (gallium) diselenide (Ci(G)S) and cadmiumtelluride (CdTe).

Amorphous silicon cell represents the first type of thin film solar cell. Unlike the first generation, silicon is not organized in a crystalline structure and its atoms assume a random position. This has an impact on its properties, increasing the bandgap energy to 1.7 eV from a value of 1.1 eV typical of Mono-Si. Thus, the absorption is improved for the wavelength in the visible light range but it is reduced for that in the infrared [28]. This type of solar cell presents an efficiency of 13.4% which is further reduced to values of 5–8% when installed outside laboratory conditions because of the fast degradation experienced when exposed to sunlight, due to the Staebler-Wronski effect.

Solar cells of the third generation are being made from a wider variety of new materials and new concepts have also been developed. New emerging concepts of solar cell are based on the use of nanotechnologies: quantum dots, hot carriers and carbon-nanotubes. However, they are still far from commercialization.

A very promising type of cells are the multi junction. Layers of different materials with different bandgap energy are used in order to increase the spectrum of wavelength effectively converted into electricity and reduce the optical/thermal losses. These cells show excellent performance and very high efficiency, up to 40%. However the manufacturing process is very expensive. Thus, the current trend is promoting its application in concentrating systems since a smaller surface area is required.

Another type of PV technology which should be considered is represented by Organic cells. These are made from semiconducting organic polymers and are currently in the research and development stage. The physics behind these new cells is still not fully understood to address the degradation and stability issues which have emerged. Further studies are also required to select the most suitable polymers, among the wide range of alternatives. In spite of their low efficiency (3–4%), they still represent an interesting option due to the established manufacturability, very low cost and the possibility of further improvements through the formation of multi-junction cells.

Table 3 summarizes the main characteristic of the different technologies.

According to the Fraunhofer Institute for Solar Energy Systems (ISE) [32], 66% of the global PV electrical production derives from polycrystalline silicon solar cells, 24% from mono-Si and 10% from thin film. Among the latter, Cd-Te contributes with a share of 59.5%, amorphous silicon 14.3% and CI(G)S 26.2%. It is worth noting that almost 90% of the solar cells on the market belong to the first generation represented by monocrystalline and polycrystalline silicon cells. Nevertheless, these technologies are not outdated since they are

Table 3
Solar Cells classification and characteristic, [15].

Generation	Technology	Commercial Cell Efficiency(%)	Best laboratory Cell Efficiency (%)	Market Share	Average commercial module cost ($\$/W$)	Area Requirements ($m^2\ kW^{-1}$)	Technology Readiness Level (TRL)
First	Monocrystalline silicon	15–19	25	24	< 1.4	7	H
	Polycrystalline silicon	13–15	21.25	65	< 1.4	8	H
Second	Amorphous silicon thin film	5–8	13.4	1.4	0.8	15	H
	CIS/CIGS thin film	7–11	20.4	2.6	0.9	10	M
	CdTe thin film	8–11	19.6	6	0.9	11	L
Third	Organic	3–4	11.1	NA	NA	NA	R&D
	Multi-junction or Tandem	25–30	40	NA	NA	NA	L

continuously improved. In particular, the former exhibits the highest efficiency among the current commercial PV cell technologies. Values of 24.7% (under STC) could be reached thanks to the improved electrical and optical design, which ensures lower reflection and better light trapping [33].

The application of some of these improvements allowed to obtain commercial cells of 17–18% efficiency [33], with a peak of almost 22.8% for the Mono-Si cells commercialized by SunPower [34]. Even if the economical investment is higher compared to poly-Si, mono-Si panels boast the longest lifetime of about 25 years and due to their higher efficiency a smaller surface area is required.

Polycrystalline shows an efficiency usually between 13% and 16%. A maximum value of 21.25% (under STC) has been reached by the Poly-Si of Trina Solar [35]. However, the simpler manufacturing process and consequently the lower cost explains their wider usage.

The behavior under different climatic conditions is of particular importance to the performance of a photovoltaic cell. The experimental study carried out by Rahman et al. [36] analyzed the dependence of efficiency and power output on various parameters: solar cell temperature, solar radiation intensity, humidity and dust. An increase of power output for higher irradiation was observed, together with a decreases of the PV module efficiency at a rate of 0.45–0.7% with a one-degree increment of module temperature.

Currently available PV technologies can convert into electrical energy only 15–20% of the solar radiation, while the remaining part is rejected heat, which is released to the ambient or trapped into the PV module, being responsible of the temperature rise of the solar cell. The possibility to recover this heat to increase the overall efficiency of the system and simultaneously reduce the module temperature is the basic concept which leads to the development of Photovoltaic/Thermal (PV/T) systems. PV/T systems can be categorized according to their design as flat plate or concentrators [37]. Concentrated Photovoltaic/Thermal systems (CPVT) represent a hybrid solution based on the combination of PV/T and concentrated photovoltaic systems. A comprehensive review of theoretical and experimental studies on CPVT is provided by Sharaf et al. [15,38]. Both strength and issues which still need to be addressed are highlighted. A review of the different flat-plate PV/T collectors instead has been presented by Riffat and Cuce [39]. The authors classified PV/T based on the type of working fluid: water, air or combined (water/air) and compared different configurations, analyzing the influence of various parameters, tube spacing, tube diameter, fin thickness and mass flow rate of the fluid, on the thermal and electrical production.

PV/T can be further distinguished into glazed and unglazed. The former allow to increase the thermal and overall energy output, while unglazed PV/T have better performance if the target is to obtain higher electrical energy production [40]. PV/T can also be classified based on the cooling fluid and type of system: pumped or thermosiphon. Reddy et al. [41] investigated single phase cooling strategies and considered both natural and forced convection. Based on the review carried out by Hasanuzzaman et al. [42] an increase of the electrical efficiency up to 15.5% can be obtained through passive cooling and a maximum of 22% with active cooling strategies. Nevertheless, the experimental and numerical analysis carried out by Chow et al. [43] in Hong Kong, highlight that thermosiphon systems perform better than pumped systems under warm climatic conditions, due to the energy savings incurred since no pumping work is required.

An environmental analysis of commercial PV technologies (multi-Si and CdTe) has been performed by Fthenakis et al. [44]. The results are reported in Table 4. The values are referred to kWh of produced electrical energy, considering an insolation of $1700\ kWh\ m^{-2} year^{-1}$, typical of Southern Europe and a system lifetime of 30 years. The environmental impact of water cooled PV/T has also been evaluated. For a 3 kW peak system with an area of 30 m^2, Tripanagnostopoulos et al. [45] determined a GWP of $12.81\ tCO_{2,eq}$: $9.36\ tCO_{2,eq}$ are from the PV Modules and BoS, while the heat recovery unit and the reflectors, used to increase the amount of incident radiation, contribute for the remaining $3.45\ tCO_{2,eq}$. The results obtained by the authors are in agreement with the analysis of Fthenakis et al. [44]. Under the same assumptions of Fthenakis et al. [44], the GWP estimated by Tripanagnostopoulos et al. [45], for the only PV Module and BoS, would be $40.6\ gCO_{2,eq}/kWh_{el}$, in the range of $21 - 45\ gCO_{2,eq}/kWh_{el}$ identified by Fthenakis et al. [44] for South Europe.

3. Storage systems

The electrical grid is subjected to important changes due to the higher penetration of distributed generation systems and the increasing amount of energy produced through intermittent renewable sources. In this scenario, the interest of the scientific community in developing innovative and efficient storage systems is growing. Storage technologies represent an important instrument to reduce the fluctuation and decouple the energy consumption from the supply, ensuring a higher stability and reliability of the grid. In recent years, many studies on the critical role of energy storage systems (ESS) for a better integration of renewable energies have been performed considering both grid-storage [47–49] and small scale distributed applications. For an accurate choice of the most suitable technology for a specific purpose, it is essential to consider the characteristics of the different storage systems, in terms of storage capability, discharge time, energy and power density, durability, efficiency, response time and costs. A technical comparison is provided by Mahila et al. [50], while Aneke et al. [51] focus on the real life applications of the various technologies.

As underlined by Akinyele and Rayudu [52], in their extensive review of energy storage technologies, the discharge timescale strongly affects the potential applications of a storage system. Long discharge time devices (up to 24 h) are suitable for energy management purposes. Examples of these systems are Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES), Thermal Energy Storage (TES) and Batteries. Medium discharge time systems (from seconds to hours) are represented by Batteries (Lead acid, Li-ion, NiCd, NiMH and Metal air) while short discharge time units (from milliseconds to minutes) are used for power quality improvement. Capacitor Storage (CS), Super Capacitor Energy Storage (SCES), Flywheel Energy Storage (FES) and Super Conducting Energy Storage (SMES) belong to this group.

In this study, the focus is on systems characterized by medium-long discharge time, since these are more suitable for energy management applications. The aim is to minimize the injection into the grid in periods of high energy production and store energy for periods of low energy generation.

In the overview provided by Amrouche in [53], energy storage systems were classified based on the form of converted energy: chemical, mechanical, electrical, thermal and electrochemical.

Chemical storage systems store the energy in the form of methane or hydrogen. The surplus of electrical energy is used to power an electrolyser to produce a pure stream of H_2, which can either be used in a fuel cell or through the addition of CO_2 further converted in a catalytic reactor into methane. Due to the high installation cost, maintenance and space requirements, methane is a valid solution only for large scale systems, with the possibility of exploiting the already existing infrastructures. The produced methane can be injected into the natural gas grid or it can be used in the highly efficient ($\eta \approx 55 - 60\%$) combined cycle power plant for electricity production. Hydrogen Energy Storage (HES) instead, even if more suitable for small scale applications, is still not attractive from a cost-effective point of view, with an overall round-trip efficiency of 40–45% [54], defining as round trip efficiency the ratio between the retrieved energy and the energy input. In their study on a small size H_2 system coupled with a fuel cell, Scozzari et al. underlined the conditions under which it could become profitable. A decrease in the maintenance and operation costs, together with a 90% reduction of the investment costs, are foreseen as the most effective to promote wide-scale deployment of this technology.

Table 4
Eco-profile of photovoltaic systems [44,46].

Emissions	Multi-Si	CdTe		Damage Factor					
	Modules + BoS [kg/kWh_{el}]	Modules [kg/kWh_{el}]	BoS [kg/kWh_{el}]	GWP [$kgCO_2$]	ODP [$kg_{CFC-11eq}$]	AP [$kgSO_{2eq}$]	EP [$kgPO_{4eq}^{-3}$]	POCP [kgC_2H_{4eq}]	Human Toxicity
CO_2	3.64E− 02	1.94E− 02	7.49E− 03	1					
As	3.27E− 08	1.46E− 09	9.94E− 09						4700
Cd	1.12E− 08	1.40E− 09	2.55E− 09						
Cr	4.39E− 08	3.55E− 09	4.00E− 08						0.57
Cr-IV	1.08E− 09	5.98E− 11	9.40E− 10						
Formaldehyde	4.61E− 08	1.29E− 08	1.03E− 07					0.443	
Ni	7.38E− 08	4.18E− 09	1.91E− 08						0.057
Nitrates, primary	1.10E− 10	9.86E− 11	3.78E− 10				0.42		0.00078
NMVOC	1.49E− 05	1.94E− 05	1.22E− 05	11	0.005			0.007	
NOx	7.16E− 08	1.46E− 12	4.72E− 05			0.7	0.13		0.78
Pb	3.32E− 07	7.56E− 08	6.08E− 08						0.79
PM10	0.00	7.06E− 11	3.74E− 08						
PM2.5	1.02E− 05	3.16E− 06	5.08E− 08						
PM2.510	9.07E− 06	1.16E− 06	1.19E− 05						
SO2	1.08E− 04	1.03E− 05	8.96E− 05			1			1.2
Sulfates, primary	2.87E− 07	2.67E− 07	8.24E− 08						
Radionuclide emissions	1.05E− 11	2.80E− 10	0.00						

Mechanical storage includes pumped hydraulic, compressed air systems and flywheels. The first two are typically used for large scale systems, even though recently small scale air compressed systems are also being investigated. Kim et al. [55] carried out an energy and exergy analysis of a micro-compressed air system, suggesting possible strategies to increase the efficiency, highlighting the advantages of quasi-isothermal compression and expansion processes compared to adiabatic ones, with the possibility of reaching a round trip efficiency of 64%. Isothermal processes are obtained injecting atomized water during the compression stage to absorb the released heat. The warm water is then separated from the compressed air and stored, in order to be re-injected during the expansion in the discharge phase. Jannelli et al. [56] proposed a new CAES design for poly-generation including also a thermal storage unit which provides an overall efficiency of 57%. Unlike other mechanical energy storage devices, flywheels are usually characterized by a short discharge time and high power supply, making them more suitable for critical loads and UPS market. Similarly to flywheels, other electrical storage devices such as super capacitors and superconducting magnetic energy storage present a low energy density and are usually applied for high-quality power. An interesting option for small scale applications is represented by thermal energy storage, due to the high energy density and the high efficiency. TES systems allow to store energy by heating or cooling a certain medium, allowing to reach an efficiency of 90% with a good insulation. On the other hand, electrochemical storage systems are based on the conversion of chemical energy into electricity. The most known type of electrochemical devices are batteries. A wide variety of batteries, with a round trip efficiency of 60–80% up to 95%, have been developed and commercialized. An overview is provided in Table 5. Together with thermal storage, electrochemical devices represent a promising option for small size systems. In Section 3.1 and 3.2, these two alternatives will be analyzed in more detail.

Table 5
Characteristics of different types of batteries [66,64].

Battery Type	Efficiency [%]	Power Density [W/kg]	Energy Density [Wh/kg]	Climatic Change [$kgCO_2/kg_{battery}$]
Lead-acid	0.70–0.90	75–300	30–50	0.9
NaS	0.75–0.90	150–230	120–250	1.2
$NaNiCl_2$ (ZEBRA)	0.86–0.88	150–200	100–140	
Ni-Cd	0.60–0.73	50–1000	15–300	2.1
Li-ion	0.85–0.95	50–2000	150–350	4.4–12.5
VRFB	0.65–0.85	166	10–35	
Zn-Br	0.60–0.70	45	30–85	

3.1. Electrical energy storage systems

A wide range of batteries are available on the market. They can be classified into primary batteries (non rechargeable) and secondary batteries (rechargeable). Vanadium Redox Batteries (VRB), Zinc Bromine (ZnBr), Sodium Sulfur (NaS), Zero Emission Batteries Research Activity (ZEBRA), Lead acid, Lithium ion (Li-ion), NiCd and NiMH belongs to the latter group.

Nair and Garimella [57] compared the various types of batteries from a technical and economic prospective. Their analysis points out the high potential of NiMH batteries in small-scale applications; however, their high initial capital cost represents the main barrier to a wider usage. A similar problem limits the diffusion of NiCd batteries while lead-acid are more common in residential applications in spite of their lower performance, due to the more competitive cost. Li-ion batteries are a promising option with a high potential to dominate the market, due to their high energy density. The current price is of 500 €/kWh [58], but a 30% reduction of battery cost already occurred from 2013 to 2014 [59] and this trend is likely to continue with a decrease of about 50% by 2030 [60]. Moreover, according to the analysis carried out by Ciez and Whitacre [61], even an increment in the price of lithium would only slightly affect the final battery price, since a 300% increase will result in a 10% higher manufacturing cost.

A novel concept of battery, still in the research and development stage, is represented by air metal batteries, which use a pure metal as anode. Advantage of this technology is the low environmental impact, since non toxic materials are used, but the recharging process is still representing the main drawback [62]. In same cases, the anode needs to be replaced mechanically even though electrically rechargeable systems are being developed. An extensive analysis of the electrochemical behavior of metallic anode materials (Li, Zn, Al, Mg, Na) is provided by Kim et al. [63].

The main characteristics of different types of batteries, efficiency, power density, energy density and environmental impact are reported in Table 5. The environmental impact is based on the life cycle analysis (LCA) performed by McManus [64]. The LCA of lead-acid batteries has also been performed by Rydh [65]. The author estimated a value of 24 gCO_2/kWh considering a lifetime of 20 years (7300 cycles).

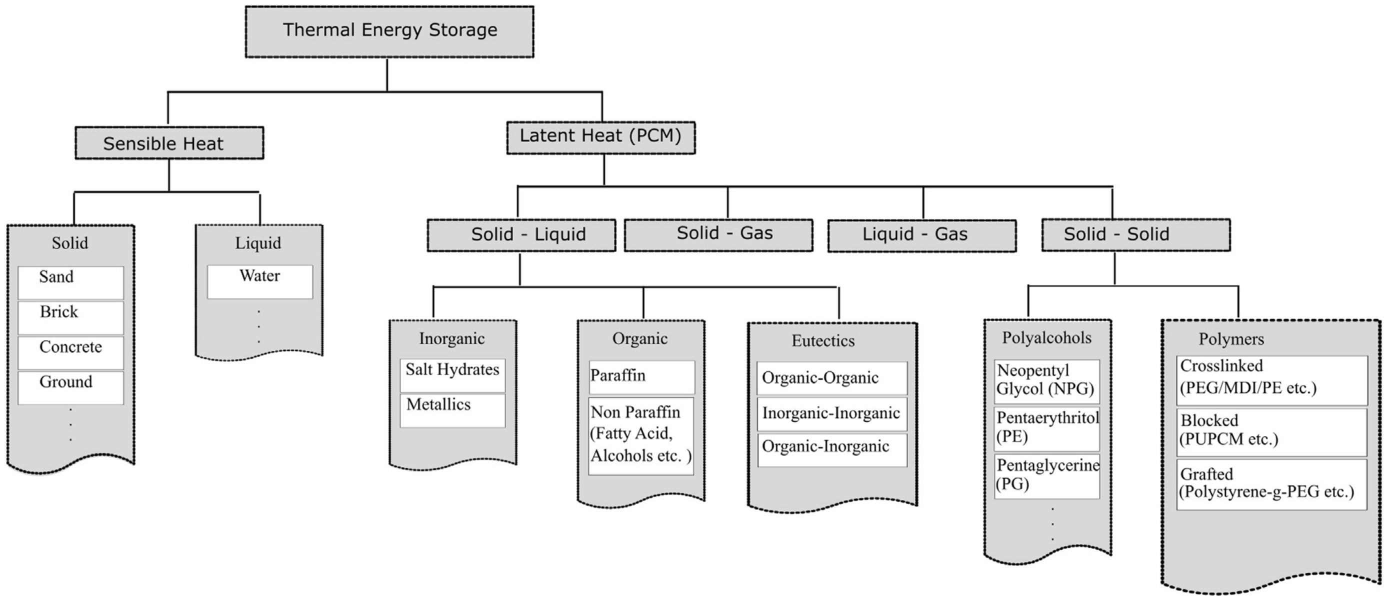

Fig. 1. Phase Change Materials (PCM) Classification. Adapted from [73,74].

3.2. Thermal energy storage systems

Thermal Energy Storage systems allow to store energy by heating or cooling a storage medium such that the stored energy can be used for various applications (space heating, cooling and hot water production) for both residential and industrial systems. However, unlike other storage medium, TES systems should be located in proximity to the end-user to reduce the thermal energy losses. TES systems can be classified into sensible and latent thermal storage.

3.2.1. Sensible thermal storage - STS

Sensible thermal energy storage is obtained by transferring heat to a certain medium, which increases its temperature. The stored energy depends on the amount of material (m), its heat capacity (c_p) and the temperature increment according to:

$$Q = \int_{T_i}^{T_0} mc_p dT \tag{2}$$

Water is typically used for temperatures below 100 °C, due to its properties: higher heat capacity, low price and availability. At higher temperatures, molten salt or oils are required due to their higher phase transition temperature. Solid material like rocks or brick can also be used, in packed beds or structured systems, usually for air heating purposes [67–69]. The cost of these systems is typically in the range of 0.1–10 €/kWh, with a capacity of 10–50 kWh/ton and an efficiency of 50–90% depending on the insulation [70].

3.2.2. Latent thermal storage - LTS

Unlike conventional sensible heat, latent heat storage is based on the energy absorbed and released during the phase change of a material. The energy stored can be determined by Eq. (3).

$$Q = \int_{T_0}^{T_{pc}} mc_{p_1} dT + m\lambda + \int_{T_{pc}}^{T_f} mc_{p_2} dT \tag{3}$$

where T_0 and T_f are the initial and final temperature of the medium, T_{pc} is the temperature at which the phase change occurs, c_{p_1} and c_{p_2} represent the heat capacity of the two phases and λ indicates the latent heat. Latent heat is usually higher than sensible heat, leading to higher energy densities, with a consequent reduction of the weight and volume required for the same amount of stored energy. However, many phase change materials (PCM) show a lower single-phase heat capacity compared to water or other sensible storage medium. A proper design of the system is then required, to operate in a narrow range of temperatures close to the PCM melting temperature, in order to maximize the benefits of latent storage systems. The importance of an accurate design and selection of the storage material has been further highlighted by the study of Talmatsky and Kribus [71]. The authors obtained an extremely surprising result, underlining the possible limitation of using PCM for domestic hot water production. They performed a numerical analysis with different types of PCM and evaluated the performance of a storage tank containing both PCM and water. During night time, the PCM releases the stored heat, determining an increment of the water temperature with consequently higher thermal losses, due to higher temperature difference between the water and the surroundings. Thus, the advantages obtained during the day were counterbalanced by the thermal losses at night. The study of Kousksou et al. [72], even though confirmed the results of Talmatsky and Kribus underlined the crucial importance of an accurate choice of the material with a suitable melting temperature to reduce this side effect for the specific system under analysis.

A wide variety of PCM characterized by a large range of melting temperatures, are available. Sharma et al. [73] highlight the main characteristics that should be considered for proper selection of the material to be used and the design of the storage system. The authors point out the importance of kinetic and chemical properties to prevent supercooling phenomena and avoid problems of chemical instability, toxicity and fire hazard. Among physical properties, a high density would be a desirable quality to keep the storage tank smaller, while a low vapor pressure and a low density variation are necessary requirements to avoid safety issues. For these reasons, even if different phase change materials could be considered: liquid-gas, solid-gas, liquid-solid and solid-solid, only the last two options are considered in practice. In the case of solid-solid, no phase change occurs but the solid modifies its crystalline structure, such as the solid-to-solid PCM polymers. Liquid-to-solid phase change materials can be classified in Inorganic, Organic and Eutectics, as shown in Fig. 1.

Organic PCMs are composed of long chains of carbon and hydrogen. The higher the carbon content, the higher is the latent heat. Organic PCMs can be distinguished into Paraffin and non-Paraffin types, which include fatty-acid, alcohols etc. Compared to other PCM, organic materials show a good chemical stability and higher latent heat but poor physical characteristics with a low density, low thermal conductivity and flammable.

Inorganic PCMs are non-flammable and boast higher energy density

Table 6
PCM with a melting temperature in the range of 0–7 °C, suitable for space cooling [74,77].

PCM Material	Type	Melting Temperature [°C]	Latent Heat [$kJkg^{-1}$]	Latent Heat [MJm^{-3}]
H_2O		0	333	333
RT3	Paraffin	3	198	
RT4	Paraffin	4	182	
RT5	Paraffin	5	198	
RT6	Paraffin	6	175	150
MPCM(6)	Paraffin	6	157–167	
ClimSel C7	Salt solution	7	130	

and thermal conductivity while they suffer from low chemical stability. The risk of phase segregation and supercooling represent a main drawback hence techniques based on the addition of nucleating agents are used.

Eutectics PCMs consist of a mixture of Organic-Organic, Inorganic-Inorganic or Organic-Inorganic materials and are used to obtain the desired melting temperature.

The review carried out by Agyenim et al. [75] highlights that most of the studies focus on PCMs with a melting temperature in the range of 0–60 °C suitable for most domestic applications, while only few works refer to medium or high temperature more suitable for solar cooling. Commercially available PCM materials are reported in Table 6–8. They are classified based on their melting temperature and possible applications. A more exhaustive list of PCM materials is provided by Cabeza et al. [76] and Veerakumar et al. [74].

The main drawback of PCM is the low thermal conductivity, with consequently longer charging and discharging times. Pere et al. [79] compared the performance of two different storage systems: a water tank and a PCM tank, filled with a commercial macro-encapsulated PCM (salt hydrate (S10) with a phase change temperature of 10 °C). The results show that the PCM tank was able to supply 14.5% more cooling and maintained the indoor temperature within comfortable levels 20.65% longer than the water tank. However, it needed 4.5 times longer to charge the tank. Different strategies have been investigated to enhance the heat transfer. The experiments and proposed techniques are accurately discussed by Agyenim et al. [75], which also pointed out the lack of a unified standard method and procedure for testing PCM, making a proper comparison difficult. Among the different options to increase the conductivity, embedded nano-structures of metal oxides, micro/macro encapsulation and shape stabilized PCM should be considered [77,74]. Mettawee and Assassa [80] suggested the use of alluminium powder embedded in paraffin wax to improve its thermal response. The authors obtained a 60% decrease of the charging time and a mean daily efficiency of 82–94% for the composite material, while for pure paraffin only values of 32–54.8% could be reached.

Table 7
PCM with a melting temperature in the range of 27–50 °C, suitable for space heating & DHW [76,77].

PCM Material	Type	Melting Temperature (° C)	Latent Heat ($kJkg^{-1}$)	Thermal Conductivity ($Wm^{-1}K^{-1}$)	Latent Heat (MJm^{-3})
STL 27	Salt hydrate	27	213	1.09	
RT 27	Paraffin	28	179	0.87	
RT 30	Paraffin	28	206		
E28	Salt hydrate	28	193	0.21	148
TH 29	Salt hydrate	29	188	1.09	284
E30	Salt hydrate	30	201	0.48	262
RT 32	Paraffin	31	130		
Climsel C32	Salt hydrate	32	212		
E32	Salt hydrate	32	186	0.51	272
A32	Aliphatic	32	145	0.21	123
Suntech P116	Paraffin wax	43–56	266	0.24	
RT 40	Paraffin	43	181		
RT 42	Paraffin	43	150	0.2	
Paraffin 44	Paraffin	44	167		
E44	Salt hydrate	44	105	0.43	166
RT 41	Paraffin	43	150	0.2	
STL 47	Salt hydrate	47	221	1.34	
Climsel C		48	227	1.36	
E48	Salt hydrate	48	201	0.45	336
E50	Salt hydrate	50	104	0.43	166

Table 8
PCM with a melting temperature in the range of 70–180 °C, suitable for solar cooling [76–78].

PCM Material	Type	Melting Temperature (° C)	Latent Heat ($kJkg^{-1}$)	Thermal Conductivity ($Wm^{-1}K^{-1}$)	Latent Heat (MJm^{-3})
Climsel C70		70	194	1.70	
E71	Salt hydrate	71	123	0.51	208
E72	Salt hydrate	72	140	0.58	233
PCM 72	Salt hydrate	72			
RT 80	Paraffin	81	140	0.2	
PK 80	Paraffin	81	119	0.2	
E83	Salt hydrate	83	152	0.62	243
E89	Salt hydrate	89	163	0.67	253
TH89	Salt hydrate	89	149		229
RT 90	Paraffin	90	163	0.2	
RT 100	Paraffin	99	137	0.2	
E117	Salt hydrate	117	169	0.70	245
X130	Solid-Solid	130	260	0.360	333
A133	Organic	133	126	0.230	111
A144	Organic	144	115	0.230	101
A155	Organic	155	100	0.230	90
A164		164	306		459
X165	Solid-Solid	165	230	0.360	300
X180	Solid-Solid	180	280	0.360	372

Alternative strategies to enhance the heat transfer are based on micro/macro encapsulation. This method consists in filling PCM in capsule, preventing the mixing of PCM and heat transfer fluid. Another option is represented by shape stabilized PCMs. It is based on the use of two materials: a working material which undergoes phase change and a supporting material which remains in the solid phase.

Compared to sensible heat storage, the cost of latent heat is higher, 10–50 euro/kWh, but they are characterized by higher capacity 50–150 kWh/ton and an efficiency of 75–90% [70].

4. Heat pump

The European Directive 2009/28/EC states the eligibility of the heat pump as a renewable energy source, provided that the minimum requirements and criteria established by the 2007/742/EC are fulfilled. Fig. 2 shows the basic principle of operation of a heat pump. It is essentially a reverse Carnot thermodynamic cycle, which transfers heat from a low temperature heat source to a high temperature heat sink on condition that energy is provided. The energy is required to drive the compressor to pressurize the refrigerant. The high pressure and temperature vapor obtained at the compressor exit, is then condensed and passes through a lowering-pressure device, e.g. expansion valve or capillary tube. The refrigerant in the liquid phase is then sent to a heat exchanger where it evaporates, absorbing heat from the energy source so as to restart the cycle.

The greater is the temperature difference between the two sources, the higher is the required compressor energy, which results in a reduction of its performance. The coefficient of performance (COP) is an important indicator used to describe the performance of heat pumps and is defined as the ratio between the useful heat transfer (Q_u) and the energy input to drive the heat pump (P_c).

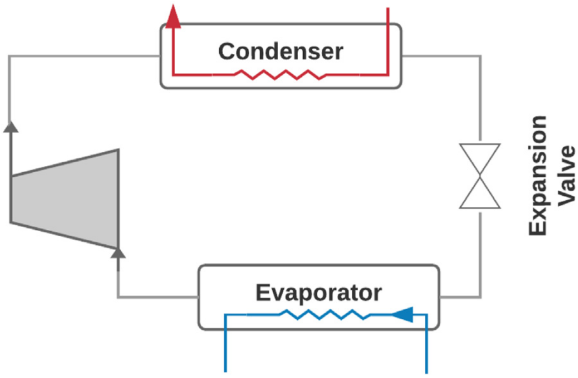

Fig. 2. Vapor compression cycle.

$$COP_{heating} = \frac{Q_u}{P_c} \tag{4}$$

Another important parameter is the seasonal performance factor (SPF) defined as the ratio between the energy output and input over a typical season. The European Directive 2007/742/EC states that only heat pumps with a $SPF > 1.15/\eta$ can be considered as renewable energy sources while the European Directive 2009/28/EC defines η as "the ratio between total gross production of electricity and the primary energy consumption for electricity production". According to the 2013/114/EU Commission Decision of the 1st March 2013 [81], the η value to be used towards 2020 is 0.455 determined based on the EuroStat data for 2010. Thus, a value of SPF above 2.5 is required.

Chua et al. [82] provide an overview of the most recent strategies aimed to increase the performance of heat pumps. In particular, the authors point out the potential reduction by 80% of the electrical energy consumption which can be obtained by improving the compressor technology. Better performance can be ensured by the use of multistage cycles, based on two or more compressors in series, and an appropriate choice of the interstage pressure. If two stages are used, the intermediate pressure is chosen to obtain the same compression ratio in each stage. The introduction of scroll compressors represented also a turning point, due to the efficiency enhancement compared to reciprocating compressors by almost 10%.

Heat pumps can be classified based on the heat source/sink as: ground source [83], air-to-air, air-to-water [84] and water-to-water [85]. Air-to-air is the most common type of heat pump which relies on air as energy source and sink. On the other hand ground source heat pumps use the ground as energy source with the advantage of a more constant temperature over the year, warmer in winter and colder in summer compared to the air temperature.

Heat pumps can be further classified based on the used refrigerant. R22 is the most widely used, due to its thermodynamic properties and the possibility of reaching high coefficients of performance. However, alternative refrigerants are considered in order to reduce the ODP such as R410a. Nevertheless, even though the ODP is lower, the GWP is similar (1730 vs 1700 $kgCO_{2,eq}$ for R22). Other possible alternatives are R134a, R407 or natural refrigerant like R744 (CO_2). A comparison between R407C and CO_2 has been performed by Byrne et al. [86]. Even if CO_2 heat pumps are characterized by a lower total equivalent warming impact (TEWI), they present lower efficiency and higher costs when compared to HFC heat pumps. Recently, heat pumps operating with R32 have been introduced into the market. R32 shows a low ODP and almost a three times lower GWP (675 $kgCO_{2,eq}$) than R22.

4.1. Hybrid vapor compression cycle

A particular type of heat pump is the hybrid vapor compression heat pump, shown in Fig. 3. Compared to conventional ones, a solution is used rather than a pure fluid. In the desorber, the most volatile component evaporates, due to the heat provided by the low temperature source. The obtained refrigerant in the vapor phase is compressed, while the liquid weak solution is pumped to the absorber/condenser, where heat is released because of the vapor absorption into the weak solution. The strong solution at the absorber outlet passes through an expansion valve and is sent to the desorber again to restart a new cycle. In order to increase the efficiency of the system, a heat exchanger is used to pre-heat the weak solution. Even though literature is not rich as for conventional heat pump, different experimental studies have been carried out to analyze the performance of this system. Kim et al [87] investigated the performance of a hybrid heat pump operating with a mixture of ammonia/water to produce high temperature heat (90 °C) from waste heat (50 °C). The laboratory scale experiments which were performed have underlined the crucial role of the ammonia concentration on the refrigerant properties (density, pressure etc.) and consequently on the system performance. The authors highlighted the possibility to cover a wide range of operating conditions through a proper variation of the concentration. In particular, it was observed that an increase of the ammonia concentration leads to higher inlet temperature in the absorber. Thus, higher temperature of the secondary fluid can be obtained. Beside ammonia/water, other mixtures have been investigated. Kim et al. [88] carried out laboratory scale experiments using R32/R134a, while Satapathy [89] considered a mixture of R22/DMETEG to analyze the possibility of simultaneous heating and cooling production at a temperature of 70 and −4 °C. These studies highlight the potential of this technology in overcoming some limits of the conventional heat pump, allowing a higher temperature lift. Nevertheless, they are still far from being considered a mature technology and require further investigation in order to ensure a good reliability. Different possible mixture of refrigerants should also be tested to determine the best option for the different temperature range of application, still considering that fluid with a low environmental impact should be preferred.

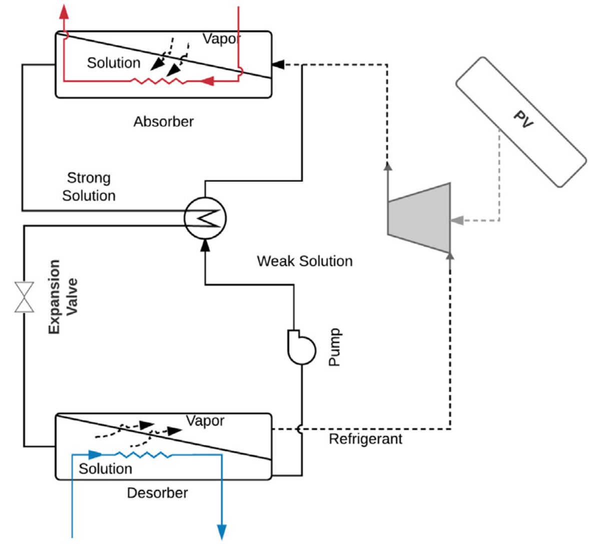

Fig. 3. Schematic representation of a Compression-Absorption Heat Pump. Adapted from [87].

5. Solar cooling

An overview of the market status of solar cooling systems is provided by Allouhi et al. [90]. The authors highlight that 82% of the installations are absorption chillers, 11% adsorption units and 7% desiccant systems. These systems are gaining attention due to the concurrence of cooling demand and available solar radiation. Nevertheless, they are mainly used in medium-large scale applications in the

commercial and industrial sector while only a few manufacturers produce small-scale absorption chillers. Among them Climatewell [91] and Rotartica [92] should be mentioned. They are partners in the Solarcombi + project [93] to promote the use of small scale sorption chillers. The single effect Water/LiBr system, developed and commercialized by Rotartica, represents the smallest unit available on the market, with a nominal cooling capacity of 4.5 kW and a COP of 0.62, which can provide from 2 kW to 8 kW depending on the operating conditions.

The market of adsorption systems is dominated by the Nishiyodo Kuchou, which developed and produced the first adsorption chiller. Among the manufacturers for small scale applications, SorTech AG [94] and Invensor [95] are the main ones. The former produces both water-silica gel systems, with a nominal cooling capacity of 16 kW and a maximum COP of 0.65, and water-zeolite of 11 kW with a maximum COP of 0.53. Invensor provides water-zeolite chillers of 10 kW and 18 kW, with a COP of $0.65 - 0.7$ and 0.55 respectively.

5.1. Absorption systems

Absorption systems represent the most promising option among solar cooling technologies. They have been widely investigated [96–99]. These systems rather than using an electrically driven compressor, are based on the affinity of two substances: the absorbent and the refrigerant. At low pressure and temperature the refrigerant is absorbed and the obtained solution is pumped to the generator where, at higher temperature and pressure the refrigerant is desorbed. The vapor refrigerant is sent to the condenser while the weak solution is returned to the absorber. Different pairs of refrigerant/absorbent have been investigated and a detailed summary is provided by Leonzio [100]. Nevertheless, Water/LiBr and Ammonia/Water are the most commonly used. A typical single effect absorption cycle is shown in Fig. 4 and the connections with a thermal collector and a hot storage tank are also highlighted.

The selected type of collector, as well as the thermal storage medium, strongly depend on the specific pair of refrigerant and absorbent used. Ammonia/Water chillers require high temperature at the generator in the range of 130–170 °C, while for Water/LiBr temperatures as low as 80–100 °C are suitable. These temperature values can be obtained with conventional FPC while to reach the higher values required by the Ammonia/Water chiller, ETC are necessary. Similarly to heat pumps, the performance of absorption systems can be described by the coefficient of performance (COP), defined as the ratio of the extracted heat from the evaporator (Q_e) to the energy provided as both thermal energy at the generator (Q_g) and electrical energy (W_{el}) due to the circulation pump (Eq. (5)). The latter contribution is usually neglected.

$$COP = \frac{Q_e}{W_{el} + Q_g} \tag{5}$$

Single effect absorption chillers based on Water/LiBr allow to obtain COP of 0.6–0.8, compared to 0.5–0.6 reached by Ammonia/Water chillers.

To enhance the performance of absorption systems a solution heat exchanger, to pre-heat the strong solution before entering the generator, can be used, as illustrated in Fig. 4.

5.1.1. Double effect absorption

Double effect absorption chillers consist of two generators operating in series Fig. 5. Heat is provided by a thermal collector to the high temperature generator (140–180 °C), while the second generator, operating at lower temperatures (90 °C), is heated recovering the rejected heat from the high temperature condenser. This system is characterized by a COP of 1.1–1.2 [96] and based on this approach, triple effect systems have also been developed with a COP of 1.6–1.7 [101].

5.1.2. Half effect absorption

Beside single and double effect, half effect absorption systems shown in Fig. 6 have also been investigated. The advantage of this configuration is represented by the possibility of using lower temperature heat sources, in the range of 55–75 °C, but the COP is also reduced to a value of 0.33–0.36 [96].

5.2. Adsorption

Adsorption systems are based on the physical or chemical interaction between the molecules of refrigerant and the adsorbent surface. The adsorbent material is contained in two compartments connected with the evaporator and the condenser. One compartment is heated and the consequent temperature increase determines the desorption of the refrigerant released in the vapor phase, while the other compartment of adsorbent particles is cooled to favour vapor adsorption, maintaining a low pressure in the evaporator. When the adsorbent beds are saturated, their operation is reversed. In Fig. 7, a schematic diagram of an adsorption system is shown. This system allows a more continuous operation compared to a single bed reactor characterized by an

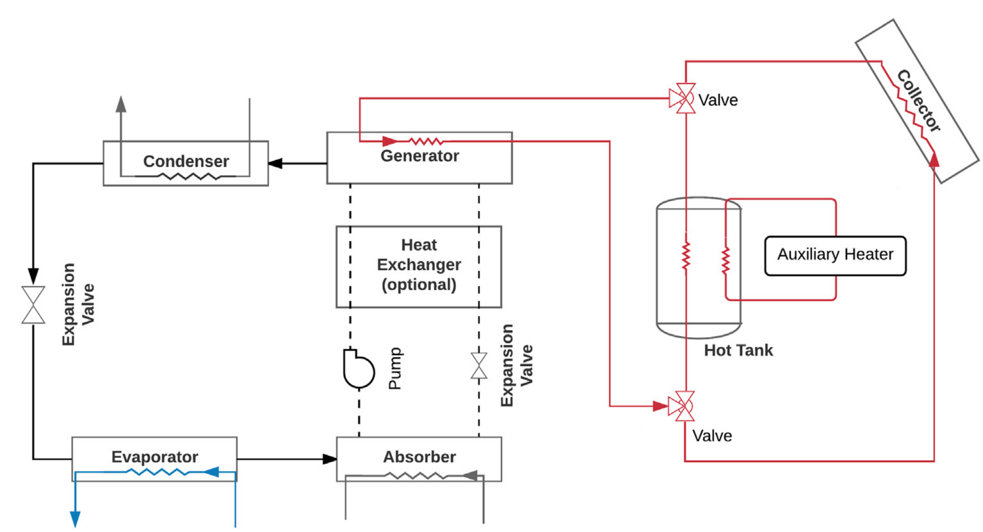

Fig. 4. Single effect Absorption Scheme with a heat exchanger.
Adapted from [96].

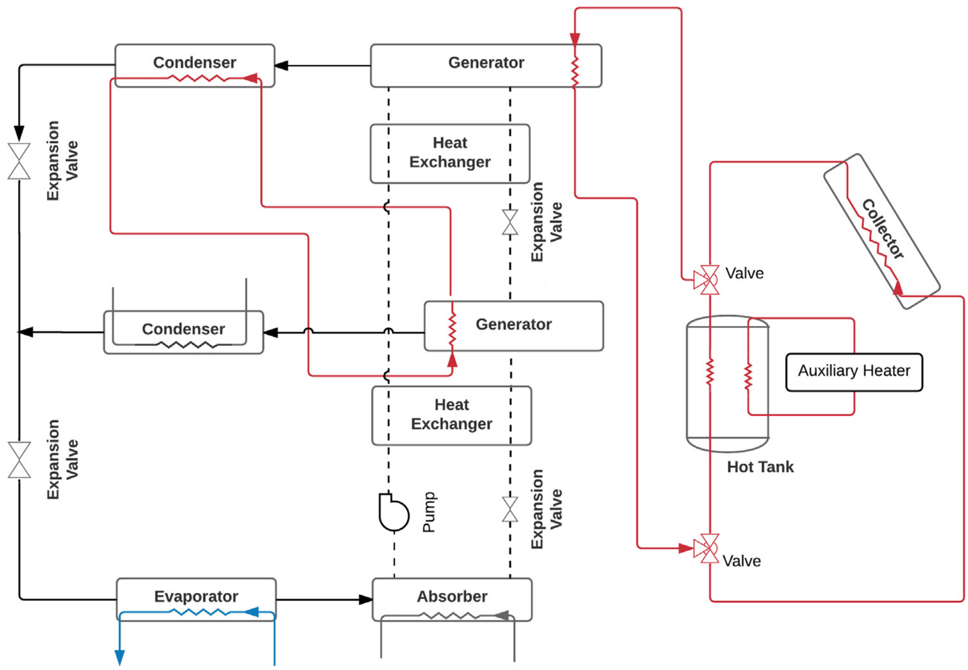

Fig. 5. Double effect Absorption Scheme with heat exchangers.
Adapted from [96].

intermittent cycle [102].

Chilled water is produced at the evaporator while a heat source (at temperatures of 60–85 °C [103]) is required to heat the desorber. Unlike conventional heat pumps, adsorption systems do not require electrical or mechanical energy, but only thermal energy. The heating source can be a conventional boiler or a solar thermal collector. An overview of the different options of coupling the adsorption systems with FPC, ETC and CPC and the results obtained by various authors are provided by Goyal et al. [104]. The selected collector type depends on the temperature required and therefore on the refrigerant/adsorbent pair used. Silica gel-water, activated carbon-ammonia or methanol, zeolite-water/ammonia are the most promising working pairs. They have a strong influence on the operation and performance of the adsorption system. A review of adsorption cooling systems with silica gel and activated carbon is presented by Sah et al. [105]. In spite of the advantages, silent operation and low environmental impact of the refrigerant/adsorbent pair, these systems are still not competitive due to the low COP and high initial cost. The high temperature variation of the packed beds during the adsorption and desorption stage is responsible of the low efficiency of these devices, together with the poor heat and mass

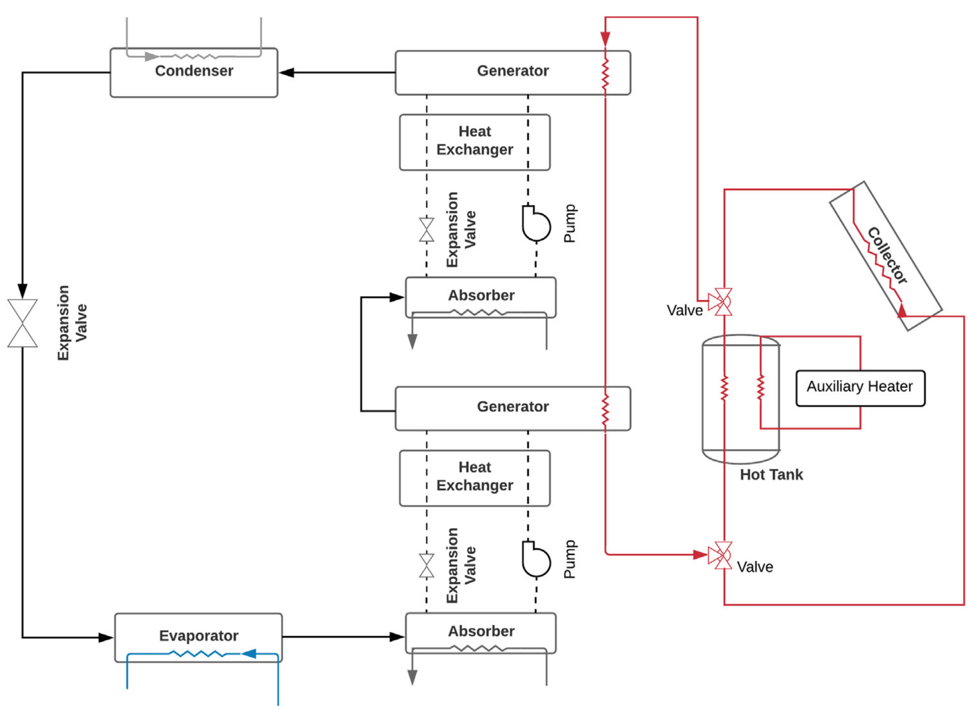

Fig. 6. Half effect Absorption Scheme with heat exchangers.
Adapted from [96].

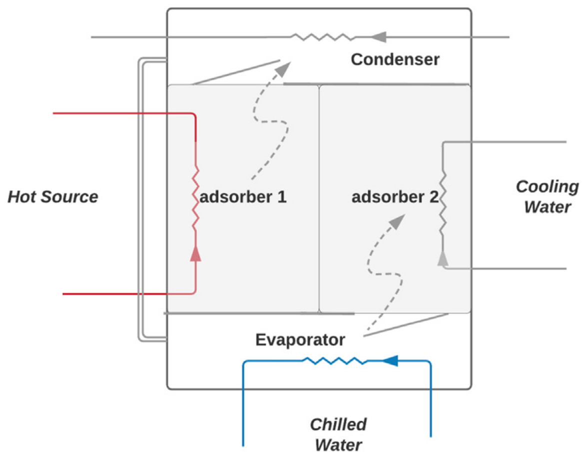

Fig. 7. Adsorption Scheme.

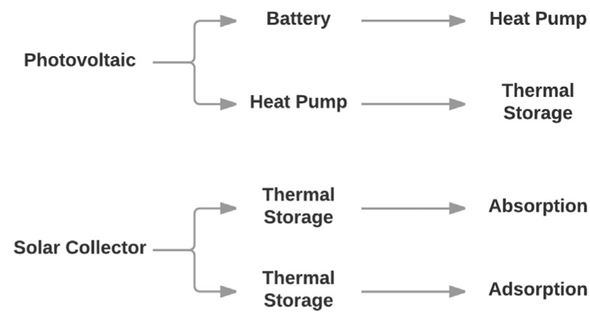

Fig. 8. Alternative options to provide electricity, heating and cooling from solar source.

transfer which occurs at the adsorption surface. Goyal et al. [104] provide a description of innovative approaches to overcome the limitation of this technology and increase the performance of these systems through mass recovery adsorption, thermal wave, convective thermal wave, multistage and cascade cycle.

A summary of the advantages and disadvantages of adsorption systems and of the other cooling technologies is provided in Table 9.

6. Comparison of the different options

The different routes to produce electrical and thermal energy from solar source are summarized in Fig. 8.

PV is a mature and well-established technology for electricity production. In parallel to the widespread of PV systems, which has been accelerated by the cost reductions and market development, the awareness of the versatility and reliability of PV electric supply systems has also increased. According to the current practice, the excess electricity from PV is injected into the grid. However, as previously mentioned, new strategies have been investigated to reduce the grid load.

The main trend is based on the use of batteries to store the excess electricity produced. As underlined in Section 3.1, batteries can provide a round trip efficiency from 60 up to 90–95% [106,62]. In the following analysis, an average value of 75% has been considered.

An interesting alternative is represented by the possibility of storing the surplus of energy as thermal energy, even more if it is considered that in the residential sector, according to Urge-Vorsatz et al. [107], the thermal energy required can account for a consistent share of the overall building demand, typical ranges are from 18% to 73%, with a strong tendency to further increase due to the higher comfort level expectations. In this scenario, the excess electricity is used to power a heat pump, thus obtaining with an extremely efficient process ($COP = 2 - 6$) the required thermal energy, which can be stored as sensible or latent heat. Thermal storage reduce both the electricity demand in periods of low energy production and the electricity injected into the grid in periods of high solar radiation, thereby decoupling the energy supply from the demand. Moreover, the use of two tanks for hot and cold storage would be suggested in order to obtain an effective reduction in electricity demand, smoothing the load profile. This alternative could be beneficial mainly in buildings with a high thermal demand, bypassing other intermediate conversions and providing it directly in the required form.

Different variants of this option have been investigated. Fatouh [85] analyzed the performance of a water-to-water heat pump coupled with two storage tanks and operating with R134a. The experimental studies performed for a wide range of operating conditions, show the possibility to reach COP of $3.7 - 4.9$ in simultaneous operating mode.

Other studies show the advantage of PV systems coupled with heat pump and thermal storage. A one year experimental study of a HP powered from a photovoltaic panel for DHW production has been performed by Aguilar et al. [108]. The results highlight the high average seasonal efficiency (SPF) of 3.42 and the possibility to lower the non renewable energy consumption by 58% (from 4.17 kWh_{PE}/day to 1.74 kWh_{PE}/day) when the system is compared to a natural gas boiler. Furthermore, the authors point out the importance of some parameters, i.e. thermal accumulation volume, DHW demand and solar insolation, to optimize the design and maximize the use of the produced energy.

It is worth noting that both designs, with battery (Fig. 9) and thermal storage (Fig. 10), allow flexibility of operation in a microgrid system, even more if these are coupled with a demand site management system (DMS).

On the other hand, solar thermal systems with a hot storage tank used in combination with solar cooling technologies (adsorption, absorption systems) can satisfy DHW, heating and cooling load. Seldom, there is the possibility to convey the surplus of thermal energy in a heating network and thus, the thermal energy has to be used locally.

Table 10 provides an overview of the possible options including current market availability and conversion efficiencies.

The approach used in this study is similar to that used by Lazzarin

Table 9
Advantages and disadvantages of cooling technologies. [90].

Thermal processes	Advantages	Disadvantages
Absorption	Noiseless Low amount of electrical energy required to operate the pump Environmental friendly refrigerant	High installation costs High Temperature heat source needed Crystallization risk (if LiBr-Water is used)
Adsorption	Low operation and maintenance costs Simple construction No corrosive and environmentally friendly refrigerant No mechanical and electrical energy required	High investment costs Poor mass and heat transfer Low COP
Heat Pump	High efficiency Low cost	Environmental impact of the refrigerant (ODP and GWP) Higher amount of electrical energy required to operate the compressor

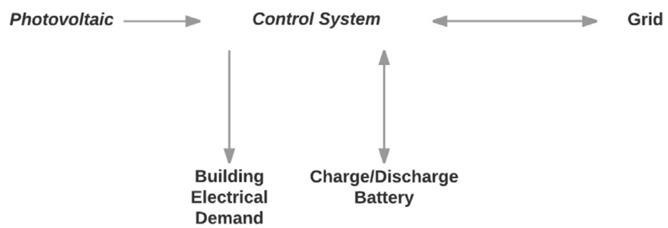

Fig. 9. Scheme of a grid connected PV system and battery.

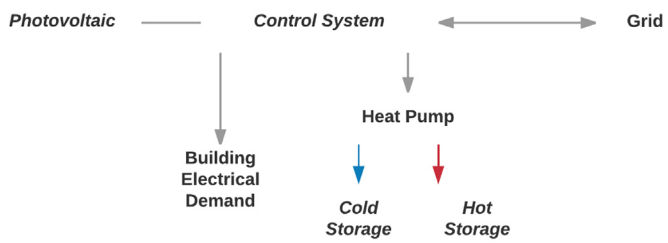

Fig. 10. Scheme of a grid connected PV system coupled with a Heat Pump and Thermal Storage.

[4], where the overall system performance (OSP) is evaluated. This is defined as the ratio between the useful cooling or heating effect and the incident solar radiation. However, in this analysis the efficiency of the storage system has also been taken into account. The values of the overall system performance for heating (OSP_h) and cooling (OSP_c) reported in Table 10 are obtained as follow:

Solar Electrical System

$$OSP_{h,c} = \frac{Q_{el}}{Q_{sol}} \cdot \frac{Q_{el,useable}}{Q_{el}} \cdot \frac{Q_{th,useable}}{Q_{el,useable}} = \eta_{PV} \cdot \eta_{Battery} \cdot COP_{HP} \tag{6}$$

$$OSP_{h,c} = \frac{Q_{el}}{Q_{sol}} \cdot \frac{Q_{th}}{Q_{el}} \cdot \frac{Q_{th,usable}}{Q_{th}} = \eta_{PV} \cdot COP_{HP} \cdot \eta_{TES} \tag{7}$$

Solar Collectors with Thermal Storage System

$$OSP_h = \frac{Q_{th}}{Q_{sol}} \cdot \frac{Q_{th,usable}}{Q_{th}} = \eta_{ETC} \cdot \eta_{TES} \tag{8}$$

$$OSP_c = \frac{Q_{th}}{Q_{sol}} \cdot \frac{Q_{th,usable}}{Q_{th}} \cdot \frac{Q_{c,usable}}{Q_{th,usable}} = \eta_{ETC} \cdot \eta_{TES} \cdot COP_{sorption} \tag{9}$$

It was considered for the Evacuated Tube Collector (ETC) an average efficiency of 0.7, a round trip efficiency of 0.9 and 0.75 for thermal storage system (η_{TES}) and battery ($\eta_{battery}$) respectively, while the coefficients of performance of heat pump and solar cooling technologies are those reported in Table 10. For the PV system, a conversion efficiency in the range of $13 - 19\%$ has been assumed, since these are typical values for silicon crystalline solar cells, which represent the 90% of the global market.

Due to the enhancement of the performance of HPs, which can reach COP of 4–5, it is evident the higher potential of PV systems coupled with a vapor compression cycle to obtain a higher conversion efficiency. Comparable performance can be obtained only through double effect absorption chillers, currently not available for small scale applications. If this is true for cooling applications, when the main target is heating production, as in Northern European Countries, solar collectors and in particular ETCs represent an efficient solution. Interesting is also the possibility of using PV/T systems, with the advantage of a simultaneous production of electricity and heat. Even if, in recent years the available range of PV/T on the market has been widened, showing an increasing diffusion, the percent of installed PV/T systems is still very small compared to thermal collectors and photovoltaics.

6.1. Installation costs

Table 11 provides an estimation of the cost of the different options in terms of kW of cooling. Photovoltaic systems coupled with heat pump and thermal storage represents the cheapest solution, followed by absorption chiller and PV with battery.

The price range for PV with battery is wide and mainly influenced by the type of battery chosen. Lead-Acid are an economically viable solution but with lower energy density compared to Li-ion. Thygesen and Karlsson [112] analyzed the use of photovoltaic technology with two different storage systems (batteries and hot water tank) under the climatic conditions of Sweden. The results show a 50% lower levelized cost of electricity (LCOE) in the case of thermal storage, 0.2 €/kWh rather than 0.4 €/kWh of batteries, for the same self-consumption. Nevertheless, the foreseen reduction of the battery prices will make

Table 10
Efficiency, flexibility and market availability of the different solar technologies.

System description	Solar-to-electrical	Solar-to-heating	Solar-to-cooling	Demand		Market
	Conversion	Conversion (OSP_h)	Conversion (OSP_c)	Electrical	Thermal	Availability
PV with Heat Pump ($COP = 3$) and battery	$13 - 19\%$	$29 - 43\%$	$29 - 42\%$	√	√	√ √ √ √
PV with Heat Pump ($COP = 3$) and thermal storage	$13 - 19\%$	$35 - 51\%$	$35 - 51\%$	√	√	√ √ √ √
PV with Heat Pump ($COP = 5$) and thermal storage	$13 - 19\%$	$59 - 86\%$	$59 - 86\%$	√	√	√ √ √ √
PV/T	$13 - 16\%$	$40 - 55\%$	–	√	√	√ √
ETC and NH_3 Absorption chiller ($COP = 0.5 - 0.6$)	–	63%	$32 - 38\%$		√	√
ETC/FPC LiBr Absorption chiller ($COP = 0.6 - 0.8$)	–	63%	$38 - 50\%$		√	√ √
ETC and Double Effect LiBr Absorption chiller ($COP = 1.1 - 1.2$)	–	63%	$69 - 76\%$		√	√ √
ETC/FPC Adsorption system ($COP = 0.3 - 0.62$)	–	63%	$19 - 39\%$		√	√

Table 11
Cost of the different solar technologies for cooling applications.

System description	Cost of the various components	Reference	Overall Cost
PV with Heat Pump and battery	PV: 2 €/W	[109]	1500–2000 €/kWc
	Vapor Compression System Including mounting and accessories: 450–600 €/kWc	[110]	
	Battery: 400–850 €/kWh	[58,60]	
PV with Heat Pump and thermal storage	PV: 2 €/W	[109]	1000–1500 €/kWc
	Vapor Compression System Including mounting and accessories: 450–600 €/kWc	[110]	
	Thermal Storage: 0.1–50 €/kWh	[70]	
ETC/FPC Li Br Absorption chiller	FPC: 150–200 €/m^2 - ETC: 250–300 €/m^2	[21]	1500–2000 €/kWc
	Chiller cost: 300–350 €/kWc	[21]	
	Auxiliary: 150–200 €/kWc	[21]	
	Cooling tower: 80–100 €/kW	[21]	
	Mountings and accessories: 200–300 €/kW (pipe, pumps, sensors etc.)	[21]	
	Installation cost: 150–200 €/kWc (10% of capital investment)	[21]	
	Storage tank: 0.1–50 €/kWh	[70]	
ETC and NH_3 Absorption chiller	ETC: 250–300 €/m^2	[21]	2500–3000 €/kWc
	Chiller cost: 500–600 €/kWc	[21]	
FPC Adsorption system	Chiller cost: 400–450 €/kWc	[21,111]	2000–2500 €/kWc
	Cooling tower: 100–200 €/kW	[111]	
	Auxiliary: 200–300 €/kWc	[111]	

them an economically feasible solution in the near future.

Sorption systems are also expensive. BoopathiRaja and Shanmugam [113] provides some suggestions to minimize the cost, using thermosiphon systems and placing the generator directly inside the storage tank to avoid heat losses. Nevertheless, the enhancement of the system performance and the development of small-size devices would represent an important step to reduce the system price and make it more competitive on the market.

The costs of solar technologies for heating purposes are reported in Table 12. It is evident that thermal collectors still represent the cheapest solution.

Nevertheless, another interesting alternative is the PV/T system with a cost of 350–500€/m^2, or referring to electrical production: 3–3.5 €/W_{el}, [114,111]. This option is more attractive if EU policy is considered. With reference to 2017, financial support is ensured to thermal solar technologies in different forms. Tax reduction mechanisms and subsides are issued in France and Germany. In Italy, a subsidy of 40% for heat pumps and up to 65% for SH&C systems and PV/T in nearly Zero Energy Buildings (nZEB) can be obtained [115]. This results in a significant reduction in the investment. Hence, the cost of PV/T is reduced to 1–1.3 €/W_{el} without considering the additional benefit of the simultaneous production of heat. Conversely, feed-in tariffs for excess electricity injected into the grid is decreasing so as to promote self-consumption and indirectly favour the use of batteries. In Malta, by contrast, only solar water heaters and water heat pumps are granted a 40% subsidy of eligible costs and up to a maximum of 400€, whilst the feed-in tariff for PV installations is very attractive, which promotes injection into the grid [116]. It is thus evident that governmental regulations have significant influence in promoting technologies.

6.2. Environmental impact

Table 13 shows the eco-profile of photovoltaic panels and solar collectors respectively based on the data reported by Fthenakis et al. and Ardente et al. [44,24]. In order to compare the values provided by the authors, a common unit of reference has been established. Assuming that the thermal collector operates with an average efficiency of 70% under the same climatic conditions specified by Fthenakis for the PV panels [44], that is an insolation of 1700 $kWh\ m^{-2}year^{-1}$, the values of the potential environmental impact per unit of kWh are calculated and reported in Table 13, considering a lifetime of 30 years for both systems. The values are referred to the thermal energy output (kW_{th}), assuming that the photovoltaic system is coupled with a heat pump with an average COP of 3. Based on similar hypothesis, the GWP of PV/T has been determined considering the results of the LCA carried out by Tripanagnostopoulos et al. [45]. However, in this case, together with the electrical energy, converted into thermal, also the heat directly produced by the PV/T was taken into account. The values, reported in Table 13, refer to a thermal efficiency of the PV/T in the range of 0.7–0.4.

In order to compare the environmental impact of the different options, their GWP has been taken into account and reported in Table 14. The values are provided in terms of cooling production. Beside the contribution of photovoltaic and thermal collectors, the environmental impact of the refrigerant fluid has also been considered and estimated as in [117,7] by:

$$E_r = C\cdot GWP\cdot(Q_{r,make-up}\cdot SL + Q_{r,loss}) \tag{10}$$

where E_r represents the emissions ($kg_{CO_{2,eq}}$) released into the atmosphere during the service lifetime (SL) of the heat pump, C is the charge of refrigerant, $Q_{r,make-up}$ is the percentage loss every year, $Q_{r,loss}$ the

Table 12
Cost of the different solar technologies for heating applications.

System description	Cost of the various components	Reference	Overall Cost
PV with Heat Pump and thermal storage	PV: 2 €/W	[109]	1000–1500 €/$kW_{heating}$
	Vapor Compression System Including mounting and accessories: 450–600 €/kWc	[110]	
	Thermal Storage: 0.1–50 €/kWh	[70]	
ETC/FPC and thermal storage	FPC: 150–200 €/m^2 - ETC: 250–300 €/m^2	[21]	500–1000€/$kW_{heating}$
	Thermal Storage: 0.1–50 €/kWh	[70]	

Table 13
Eco-profile of thermal collectors, photovoltaic systems and hybrid systems, [44,24,45].

Environmental Index	Thermal Collector	Photovoltaic Panel				Thermal/Photovoltaic	
		Multi-Si		CdTe		Panel (PV/T)	
	$[g/kWh_{th}]$	$[g/kWh_{el}]$	$[g/kWh_{th}]$	$[g/kWh_{el}]$	$[g/kWh_{th}]$	$[g/kWh_{el}]$	$[g/kWh_{th}]$
GWP $[gCO_2]$	9.5	36.6	12.2	27	9	59.8	7.5–10
AP $[gSO_{2eq}]$	6.5E− 2	0.108	3.6E− 2	0.13	4.4E− 2	–	–
ODP $[gCFC-11_{eq}]$	negligible	–	–	–	–	–	–
NP $[gPO_{4eq}^{-3}]$	9.2E− 3	–	–	6.1E− 3	2E− 3	–	–
POCP $[gC_2H_{4eq}]$	6.5E− 3	–	–	–	–	–	–

Table 14
Environmental impact of the described solar cooling technologies, [7].

System description	COP	Collector/ Photovoltaic $[gCO_2/kWh_{cooling}]$	Refrigerant	Storage System	Indirect Effect
Multi-Si/CdTe with Heat Pump and battery	3	9–12.2	18 (5.3)	8	261
Multi-Si/CdTe with Heat Pump and Thermal Storage	3	9–12.2	18 (5.3)	66	261
Multi-Si/CdTe with Heat Pump and Thermal Storage	4	6.7–9	18 (5.3)	66	196
Thermal Collector NH_3 Absorption	0.5–0.6	19–15.8	0	132–110	540–450
Thermal Collector LiBr Absorption	0.6–0.8	15.8–11.9	0	110–83	450–338
TC Adsorption	0.3–0.62	32–15.3	0	220–106	900–435

percentage loss at the end of the service lifetime and GWP is the Global Warming Potential for the specific refrigerant. Florides et al. in [117] estimated a value of 18 g_{CO_2}/kWh for a heat pump operating with R22. It is worth noting that due to the high ODP of R22, alternative refrigerants are used. Reviews and life cycle impact assessment analysis of various refrigerant are available in literature, [118,119]. Currently, the most widely used refrigerant is R410a, with a lower ODP but similar GWP to R22, [118]. Manufacturers like Panasonic and Daikin introduced in the market R32 operating vapor compression systems with a GWP of 675 $kg_{CO_{2,eq}}$, to reduce the environmental impact. A comparison between R410a and R32 has been performed by Cho et al. [120], showing a reduction of optimal charge of refrigerant by 26%. Based on this data and considering Eq. (10), it would be possible to reduce the environmental impact of the refrigerant from 18 g_{CO_2}/kWh to 5.3 g_{CO_2}/kWh. Moreover, as carried out in Otanicar et al. [7] the indirect effect is also considered since it accounts for the emissions due to back-up form of energy. According to the LCA performed by Heikkila et al. [121,122], the main contribution of heat pump to the environmental impact is related to the energy required by the compressor during its usage. The emissions per KWh of produced electrical energy are assumed to be 784 g_{CO_2}/kWh, [7] while, for the solar thermal system, a natural gas boiler has been considered as back-up source. Assuming an efficiency of 85% and a calorific potential of 42900 kJ/kg_f for the SNG, a value of 270 g_{CO_2}/kWh is obtained. The GWP associated with the storage system has also been taken into account. According to the LCA carried out by McManus and Rydh [64,65] the GWP for Lead-acid batteries can be considered to be 24 g_{CO_2}/kWh, while a value of 66 g_{CO_2}/kWh has been used for thermal storage, as reported by Otanicar et al. [7].

PV systems with heat pumps and batteries show to have the lowest environmental impact followed by PV with thermal storage, while sorption units have a higher GWP in spite of the use of a more environmental friendly refrigerant, as described by Otanicar [7]. The main limit of solar cooling technologies is represented by the low coefficient of performance. Further studies in this direction would be beneficial.

7. Conclusions

An overview of the main solar technologies has been provided and various process chains to produce electrical and thermal energy have been analyzed. However it is difficult to provide a definitive answer to which would be the best technology. Whether one should use PV and heat pump coupled with battery or TES system, or solar cooling or a side by side system is strongly dependent on the location, climatic conditions, buildings' load and government policy. For these reasons, an accurate and deep analysis of the overall system for the specific application and location should be promoted to determine the best solution which suites the user's needs. Nevertheless, the preliminary comparison carried out in this work shows that:

- The choice of the best technologies to be used, strongly depends on the particular application and the main user objectives. For heating purposes, solar collectors still represent the best solution, in particular evacuated tubes. On the other hand, for cooling purposes, photovoltaic panels coupled with a heat pump are a very promising option with excellent performance, low cost and low environmental impact. This can be mainly attributed to the more advanced manufacturing processes and the increased efficiency of both PV panels and heat pumps.
- The market survey of vapor compression cycle shows that the majority is still based on the use of Hydrofluorocarbon (HFC) and further reduction of the greenhouse gas (GHG) emissions can be achieved with new type of refrigerants, but attention should be paid to their effect on the heat pump performance. The electrical energy consumption during heat pump operation represents the main source of GHG. At a 26% reduction of the COP from 3 to 2.2 corresponds a 36% increase of the GWP.
- The COP of the various solar technologies is a key factor which affects not only the efficiency performance but also environmental and economical aspects.
- Even though they are still in the research and development stage, hybrid heat pumps have the potential to reach very high performance with COPs of 9 as estimated by Satapathy et al. [89]
- The use of PV and heat pump in combination with batteries or thermal storage allow for peak shaving, reduction of the energy injected into the grid, increment of the self-consumed energy and optimal energy usage thanks to a proper integration of the overall system and an efficient energy management.
- PV systems with battery show to have the lowest GWP, but the high initial cost limit their usage, despite the reduced feed-in tariff and the higher electricity cost which makes self-consumption more attractive. A cheaper alternative is represented by PV with thermal

storage.

- PV/T systems are gaining more attention. Even if their market share is extremely small, it is expected to increase thanks to government financial support.
- Solar cooling technologies require further research to increase their conversion efficiency and are still costly but, incentives have already shown to play a central role in promoting the introduction of these systems into the market and reduce the economic gap with photovoltaic systems.

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